METHOD AND APPARATUS FOR REDUCING EFFECTIVE TRACK WIDTH THROUGH HIGHLY SKEWED HEAD ANGLES

Priority is claimed from U.S. Provisional Patent Application No. 60/232,810, filed September 15, 2000 entitled "Reducing Effective Track Width Through Highly Skewed Head Angles," which is incorporated by reference in its entirety.

FIELD OF THE INVENTION

The present invention relates to the field of magnetic storage devices, and, more particularly, to an apparatus and method for increasing track density on a magnetic storage medium, and increasing head width tolerance.

BACKGROUND OF THE INVENTION

A diagrammatic representation of a conventional disk drive, generally designated 10, is illustrated in **Fig. 1**. The disk drive comprises a disk 12 that is rotated by a spindle motor 14. Digital information is stored within concentric tracks on the disk 12 which is coated with a magnetic material that is capable of changing its magnetic orientation in response to an applied magnetic field. The spindle motor 14 is mounted to a base plate 16. An actuator arm assembly 18 is also mounted to the base plate 16. The disk drive 10 also includes a cover (not shown) that is coupled to the base plate 16 and encloses the disk 12 and actuator arm assembly 18.

The actuator arm assembly 18 includes a flexure arm 20 attached to an actuator arm 22. A head 24 is mounted near the end of the flexure arm 20. The head 24 is constructed to magnetize the disk 12 and sense the magnetic field emanating therefrom.

The head can include a single element, such as an inductive read/write element for use in both reading and writing, or it can include separate read and write elements. Heads that include separate elements for reading and writing are known as "dual element heads" and typically include a magneto-resistive (MR), or giant magneto-resistive (GMR), read element for performing the read function.

The actuator arm assembly 18 pivots about a bearing assembly 27 that is mounted to the base plate 16. Attached to the end of the actuator arm assembly 18 is a magnet 28 located between a pair of coils 30. The magnet 28 and coils 30 are commonly referred to as a voice coil motor 32 (VCM). The spindle motor 14, head 24 and VCM 32 are coupled to a number of electronic circuits 34 mounted to a printed circuit board 36, which comprise the control electronics of the disk drive 10. The electronic circuits 34 typically include a read channel chip, a microprocessor-based controller and a random access memory (RAM) device.

The disk drive 10 typically includes a plurality of disks 12 and, therefore, a plurality of corresponding heads 24 mounted to flexure arms 20 for each disk surface. However, it is also possible for the disk drive 10 to include a single disk 12 as shown in **Fig. 1**.

During operation of a conventional disk drive 10, the disk 12 is rotated about a central axis 38 at a substantially constant rate. To read data from or write data onto the disk 12, the head 24 is placed above a desired track of the disk 12 while the disk 12 is spinning. Writing is performed by delivering a write signal having a variable current to the head 24

while the head 24 is held close to the desired track. The write signal creates a variable magnetic field at a gap portion of the write element that induces magnetic polarity transitions into the desired track. These magnetic polarity transitions constitute the stored data.

Reading is performed by sensing the magnetic polarity transitions on the rotating track with the head 24. As the disk spins below the head 24, the magnetic polarity transitions on the track present a varying magnetic field to the read element. The read element converts the varying magnetic field into an analog read signal that is then delivered to a read channel for appropriate processing. The read channel converts the analog read signal into a properly timed digital signal that can be recognized by a host computer system.

As mentioned above, the head 24 may be a single element head or a dual element head. A particularly important type of dual element head is a magnetoresistive head that includes a magnetoresistive (MR) read element and a separate write element that is usually inductive. MR read elements include a small piece of magnetoresistive material having a variable resistivity that changes based on an applied magnetic field. That is, as the magnetic field applied to the material increases, the resistivity of the material, in general, decreases. In practice, the MR material is held near the desired track as a substantially constant sense current is run through the material. The magnetic field variations produced by the magnetic transitions on the rotating track change the resistance of the magnetic material, resulting in a variable voltage across the material that is representative of the data stored on the disk (i.e., a read signal). MR read elements have gained much popularity in recent years as they typically generate read signals having considerably higher voltages than those generated by inductive read elements.

A more detailed view of a dual element head, generally designated 50, used for reading and writing magnetic polarity transitions to a magnetic media is illustrated in **Fig. 2**. Referring to the figure, portions of the dual element head 50 which face the magnetic media are shown. The head 50 includes a write element 54, write gap 58, first shield 62, second shield 66, read gap 70, and magnetoresistive (MR) read element 74. It should be noted that the write element 54 typically has a width 78 which is greater than a width 82 of the read element 74. For example, the width 78 of the write element 54 might be twice the width 82 of the read element 74. As is well known in the art, this illustrates a "write wide/read narrow" type head. It will also be understood that other types of heads may be used.

As part of the writing process, a variable current is used to induce magnetic flux across the write gap 58 between the write element 54 and the first shield 62. The write element 54 and first shield 62 act as poles for an electromagnet which induces magnetic flux across the write gap 58. The direction of the variable current defines the direction in which the magnetic flux will be oriented across the write gap 58. In some simple recording systems, flux polarized in one direction across the write gap 58 will record a binary "one" on the magnetic media while flux polarized in the opposite direction will record a binary "zero." In many recording systems, a change in the direction that the flux travels across the gap 58 is interpreted as a "one" while the lack of a change is interpreted as a "zero." As the magnetic material on the disk surface 12 (illustrated in **Fig. 1**) travels under the head 50 in the direction shown by arrow 86, a series of digital "ones" and "zeros" can be written within the data track.

When reading, the magnetic polarity transitions, previously written onto the magnetic media, are coupled to the head 50 in order to recover the stored digital data. When a magnetic polarity transition in the magnetic media passes under the head 50, the read element 74 will generate a signal in response to the changing magnetic field which corresponds to a previously recorded data bit. This signal is called an analog read signal. Conversion of the analog read signal back into a digital signal is performed within a read channel, after which it is passed to an exterior environment such as a computer. During the read process, the first and second shields 62, 66 form a read gap 70 which serves to focus the flux for a particular magnetic polarity transition onto the read element 74 by shielding the read element 74 from other sources of magnetic flux. In other words, extraneous magnetic flux is filtered away from the read element 74 by the shields 62, 66.

As is well known in the art, data storage capacities in magnetic storage devices are rapidly increasing. This increase in storage capacity is in large part due to the increased recording density on the magnetic media, allowing more data to be stored per unit area on the media. As the data density continues to increase, the number of tracks per inch (TPI) increases, resulting in a decreased track width for each track. In addition to the increased TPI, the number of bits per inch (BPI) is also increasing.

The decreased track width impacts several areas of the magnetic storage device. One such area is the head. The width of the read and write elements on the head must be decreased in a similar manner as the track width, in order to continue properly reading and writing data to the data tracks. However, due to limitations in the manufacturing technology used to fabricate the head, it is becoming increasingly difficult to manufacture heads with

read and write elements that have the required width. In particular, as mentioned above, in many heads, the width of the read element is less that the width of the write element. Thus, in these type of systems, it is often particularly difficult to fabricate the read element to the appropriate width.

For example, in one current day design, the read element has a nominal width of 0.14μ, with a tolerance of 0.04μ. When fabricating a read element, traditional semiconductor fabrication processes are used. However, current day photolithographic limits in the fabrication process are roughly the same as the nominal width of the read element. Operating this close to the limits of the fabrication process can often result in heads which do not meet the nominal width and tolerance requirements of the head. As a result, it is common practice to have a number of heads fabricated, and then measure the finished product in order to determine which of the heads are acceptable. As will be understood, this can be an expensive process, due to both the time required to perform the testing of the finished product, as well as the cost of the heads which are not usable due to being out of the specified limits. Accordingly, it would be advantageous to have a head width which is greater than the limits of the manufacturing process, in order to have a more robust manufacturing process for fabricating the heads.

Another area where reduced track width impacts the head is in the signal produced when reading data from the magnetic media. As a result of the reduced track width, and the resulting decrease in reader width as described above, the aspect ratio of the MR read element increases. Referring now to **Fig. 3**, a simplified cross-sectional illustration of a MR element is now described. The read element 74 is positioned between two connecting leads

90, 94. A sense current is passed through the first connecting lead 90, as indicated by the arrow 98. The sense current flows through the MR read element 74, and then flows through the second connecting lead 94, as indicated by the arrow 106. The MR read element 74 is typically comprised of a soft adjacent layer (SAL), an insulating layer, and an MR sensor layer, and is well known in the art. As a result of the biasing properties of the SAL, in combination with the sense current, the magnetization of the MR read element 74 is deflected, with this deflection illustrated by the arrow 102. As the read element 74 passes over the transitions recorded into the magnetic media, the amount of the magnetization deflection on the read element 74 is changed, changing the resistance of the read element 74, thus either increasing or decreasing the voltage across the read element 74, which is used to determine the data stored on the magnetic media, as mentioned above.

However, as the width 82 of the read element 74 decreases, the aspect ratio of the read element 74 generally increases. The aspect ratio of the read element 74 is the stripe height 110 over the width 82 of the read element 74. In general, due to the decreased track width, the width 82 of the read element 74 decreases. However, as the width 82 decreases, the stripe height 110 is generally not reduced, resulting in an increased aspect ratio. This increased aspect ratio results in less magnetization deflection in the read element 74. This reduced magnetization deflection in turn results in an analog read signal which is also reduced. Accordingly, it would also be beneficial to have a read element 74 which has a relatively low aspect ratio.

Furthermore, while a MR type read element has been described, similar problems are encountered with GMR type read elements. As is well understood by those of skill in the art,

GMR type read elements employ additional structures to produce a fixed magnetization and a freely rotating magnetization. The analog read signal is produced based on the angle between the two magnetizations with increased aspect ratios resulting in a reduced angle between the two magnetizations. Thus, reduced aspect ratios would be beneficial in GMR type elements as well.

Another difficulty that arises from reduced track width is reduced magnetic flux from the surface of the magnetic media. As will be understood, the reduced track width results in reduced flux from the magnetic transitions. This reduced flux in turn results in a decreased signal-to-noise ratio (SNR) in the analog read signal. Accordingly, it would also be beneficial to have an increased SNR with a reduced track width.

As is known in the art, the head skew angle is generally the angle of the read and write gap relative to a radial line through the center of the disk. More specifically, the skew angle of the read element is the angle of a line parallel to the read element at the center of the read gap relative to a radial line through the center of the disk. Likewise, the skew angle of the write element is the angle of a line parallel to the write element at the center of the write gap relative to a radial line through the center of the disk. Generally, the difference in the skew angle of the read element and the skew angle of the write element is relatively small, thus the term head skew angle is used generally to cover both of these skew angles, with the understanding that the skew angles of the read element and the write element may be somewhat different. Referring now to **Fig. 4**, an illustration of head skew in a typical disk drive is now described. As indicated in the figure, the disk surface 12 has a centerpoint 100. The actuator arm 104 pivots about an actuator pivot 112, and has an arm length A (measured

from the actuator pivot 112 to either the center of the read gap or the center of the write gap). The distance from the centerpoint 100 to the end of the actuator arm 104 is the radius R. The distance from the centerpoint 100 to the actuator pivot 112 is designated as M. The head skew angle θ at a radius R can then be determined according to the following equation:

$$\theta(R) = \frac{\pi}{2} - \cos\left(\frac{A^2+R^2-M^2}{2AR}\right)^{-1}.$$

Typically, in current day disk drives, the head skew angle 124 is minimized. This is the case for several reasons. One such reason is flying height concerns of the head. Typical disk drives currently have heads fly very closely to the disk surface at a distance known as the fly height. The fly height is maintained by using an air bearing, which is created when the disk spins beneath the head. The head is designed with an air bearing surface (ABS) which acts to maintain the correct fly height when the disk is spinning. Traditionally, this ABS has been sensitive to the head skew angle 124, with increases in the head skew angle 124 resulting in a change in fly height compared to the fly height when there is zero skew. Such a change in fly height, in general, is not desirable.

Furthermore, the head skew angle 124 has traditionally been minimized in order to enable the writing of radially coherent servo information to the disk surface 12 using the head. In such systems, the disk drive may coupled to a servo track writer, which moves the actuator arm 104. The actuator arm 104 is used to write servo information. If the head has a relatively large skew angle 124, it may be difficult to write a radially coherent servo pattern, resulting in a much longer process to write servo information.

As a result, head skew angles 124 have been minimized in traditional systems, with many products having a head with a zero degree head skew angle 124 at about a midpoint 126 between an inner diameter 132 and an outer diameter 128 of the disk surface 12. Such systems commonly have a change in skew of +/- 15 degrees as the head is moved from the midpoint 126 to either the inner diameter 132 or the outer diameter 128. Products are also known which have a zero degree skew angle at either the inner diameter 132 or outer diameter 128, with the magnitude of the skew angle increasing to about 20 degrees at the opposite diameter of the disk surface 12.

Accordingly, there is a need to develop a method and apparatus for (1) improving the tolerances of the head, thus allowing for narrower track widths with fewer heads rejected for not being within specifications, (2) reducing the aspect ratio of the read element, thus allowing for an enhanced analog read signal, and (3) increasing the SNR of the analog read signal.

SUMMARY OF THE INVENTION

The present invention solves the aforementioned problems and meets the aforementioned, and other, needs. The invention provides a magnetic storage device which employs a head with a high skew angle. This allows the head to be designed such that the head width increases according to the inverse of the cosine of the skew angle. In one embodiment, the head is mounted on the flexure arm at an angle, resulting in a minimum head skew angle across all of the data tracks on the disk surface. In another embodiment, the flexure arm is mounted to the actuator arm at an angle. In yet another embodiment, the

length of the actuator arm assembly is shortened to allow a greater range of skew angles across a disk surface.

Additional features and other embodiments of the present invention will become apparent from the following discussion, particularly when taken together with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a diagrammatic representation illustrating a disk drive;

Fig. 2 is a diagrammatic representation illustrating the components of a head in a disk drive;

Fig. 3 is a diagrammatic representation illustrating a read element;

Fig. 4 is a diagrammatic representation illustrating a component of a disk drive for the purpose of illustrating head skew angles;

Fig. 5 is a diagrammatic representation illustrating a head in relation to a data track for one embodiment of the present invention;

Fig. 6 is a diagrammatic representation illustrating a skewed and non-skewed element in relation to a data track for one embodiment of the present invention;

Fig. 7 is a diagrammatic representation illustrating a disk drive and actuator arm assembly having a head mounted at an angle, according to one embodiment of the present invention;

Fig. 8 is a diagrammatic representation illustrating a disk drive and actuator arm assembly having a flexure arm mounted at an angle, according to one embodiment of the present invention; and,

Fig. 9 is a diagrammatic representation illustrating a disk drive and actuator arm assembly having a relatively short length, according to one embodiment of the present invention.

DETAILED DESCRIPTION

While this invention is susceptible of embodiments in many different forms, there are shown in the drawings and will herein be described in detail, preferred embodiments of the invention with the understanding that the present disclosure is to be considered as an exemplification of the principles of the invention and is not intended to limit the broad aspects of the invention to the embodiments illustrated.

Referring to **Fig. 5**, a diagrammatic illustration of a head 200 in relation to a data track 204 of one embodiment the present invention is now described. In this embodiment, the head 200 has a large skew angle 208 with respect to the data track 204. The large skew angle 208 results in a write element 212 and a read element 216 which are also skewed with respect to the data track 204. This large skew angle 208 results in the read element 216 having an effective width 220 with respect to the data track 204 which is narrower than the physical width 224 of the read element 216. Likewise, the write element 212 has an effective width 228 with respect to the data track 204 which is narrower than the physical width 232 of the write element 212.

Decreasing the effective widths 220, 228 of the read and write elements 216, 212 has several implications. First, the physical widths 224, 232 of the read and write elements 216, 212 may be increased relative to the track width 236. The physical width 224, 232 of the elements 216, 212 increases according to one over the cosine of the skew angle 208. For example, the head 200 may have a skew angle 208 of 60 degrees. In such a case, the physical width 224, 232 of the elements 216, 212 is double the effective width 220, 228 of the elements 216, 212. Thus, for a given track width 236, the skewed elements 216, 212 may have a larger physical width than a similar element which is not skewed. As can be understood, an element having a larger physical width is less difficult to manufacture than an element with a smaller physical width. Likewise, any tolerance required for the read or write elements 216, 212, is also increased according to the inverse cosine of the skew angle 208.

Referring to **Fig. 6**, a simplified illustration of this principle is now described. A data track 204, with a centerline 206 is illustrated, along with a zero-skew element 240 and a high-skew element 244. The nominal width 248 of the zero-skew element 240 is indicated, along with a tolerance 252 on either side of the zero-skew element 240. The high-skew element 244 has a nominal width 256 which exceeds the nominal width 248 of the zero-skew element by the inverse cosine of the skew angle 258 of the high-skew element 244. Likewise, the tolerance 260 for the high-skew element 244 exceeds the tolerance 252 of the zero-skew element 240 by the inverse cosine of the skew angle 258. As discussed above, increasing the element width and tolerance increases the margin of the manufacturing process used to fabricate the elements.

Referring again to **Fig. 5**, the head 200 also includes a first shield 264 and a second shield 268. As alluded to in the Background of the Invention, the read element 216 reads magnetic signals present in between the shields 264, 268. The skew angle 208 also results in increased effective shield spacing 272 over the physical shield spacing 276. This increased effective shield spacing 272 results in increased magnetic flux from the surface of the magnetic media available to the read head 216. This in turn results in an enhanced SNR for the analog read signal.

However, due to the increased effective shield spacing 272, the width of a bit of data stored in the data track 204 must also be increased as compared to the width of a bit of data stored in the data track 204 when the skew angle 208 is substantially less. The width of a bit of data is commonly known as the pulse width, and is well known in the art. Accordingly, the pulse width in a magnetic storage device according to this embodiment is increased as compared to the pulse width of a magnetic storage device which has a lower skew angle 208. However, the pulse width may be limited by the thermal stability of the magnetic media. When the thermal stability limit is reached, the pulse width may not be reduced any further, because the magnetic media may lose the magnetic charge. When thermal stability limits the reduction of pulse width, having an increased pulse width with a skewed head 200 may be beneficial, as the magnetic media will retain charge, and the SNR for the analog read signal is enhanced as compared to a head with a reduced skew angle.

Another effect of the increased skew angle is the stripe height. As discussed above in the Background of the Invention, it is beneficial to have a relatively low aspect ratio in an MR element. According to one embodiment of the present invention, the aspect ratio of the

MR element can be reduced by increasing the physical width of the MR element. This allows for a reduced aspect ratio when the stripe height is not adjusted, and the width of the MR element is increased. This reduced aspect ratio allows for a larger magnetization deflection in the MR element and an element which is more sensitive to magnetic flux changes. Accordingly, the analog read signal produced by such an element is enhanced. Additionally, the reduced aspect ratio allows for an increased angle between the fixed magnetization and freely rotating magnetization in a GMR type element, resulting in an enhanced analog read signal.

Furthermore, the increased skew angle 208 also allows a reduced effective track width 236 as compared to a data track which does not use a skewed head 200. As mentioned above, because of the increased effective shield spacing 272, the pulse width may be increased for the highly skewed head. Therefore, the reduced track width 236 is offset by the increased pulse width, thereby resulting in a net effect of little or no capacity gain or loss for a magnetic storage device employing this embodiment. However, as mentioned above, thermal stability of magnetic media may limit the pulse width. Thus, in an embodiment where the pulse width is limited by thermal stability of the magnetic media, the reduced track width 236 can result in an increase in the capacity of the magnetic media.

Referring now to **Fig. 7**, one embodiment is illustrated for giving a head a large skew angle. As can be observed, the head 300 is mounted at the end of the flexure arm 304 at an angle 306 relative to a centerline 307 of the actuator arm 308. The flexure arm 304 is mounted to the end of the actuator arm 308 with no significant angle. In one embodiment, the head 300 is mounted at an angle of 45 degrees relative to the end of the flexure arm 304.

This produces a skew angle 316, in one embodiment, of approximately 45 degrees at the outer diameter 320 of the magnetic media 12, and a skew angle 316 of approximately 65 degrees at the inner diameter 324 of the magnetic media 12. It will be understood that other angles 306 for mounting the head 300 on the flexure arm 304 are possible, resulting in different skew angles 316.

As will be understood by those of skill in the art, servo information which is written to the magnetic media is generally used to position the head 300 in the proper location relative to the surface of the magnetic media 12. This servo information can be written to the magnetic media 12 in a number of ways. One such method of writing this servo information is to use a servo track writer, which couples to the actuator arm assembly 312 within the disk drive and writes a radially coherent servo pattern to the magnetic media 12. However, in the embodiment of **Fig. 7**, this method will not produce a radially coherent servo pattern. Thus, in using this embodiment, the above-noted method for writing servo information is not used. Rather, an alternative servo pattern, or method of writing the servo pattern, is used. One such alternative is to introduce an alternate head to the magnetic media, which can act to write a coherent servo pattern. Another alternative is to use magnetic media which has a pre-printed servo pattern. Yet another alternative is to use a spiral servo pattern, an example of which is described in U.S. Patent Application No. 09/853,093 filed on May 9, 2001, entitled "Method and Apparatus for Writing and Reading Servo Information Written in a Spiral Fashion," which is incorporated herein by reference in its entirety.

Referring now to **Fig. 8**, another embodiment for giving a head a large skew angle is illustrated. As can be observed from the figure, the flexure arm 304 is mounted at the end

of the actuator arm 308 at an angle 328. This results in the head 300 at the end of the flexure arm 304 of the actuator arm assembly 312 having a skew angle 332. In this embodiment, the head 300 is mounted such that it is tangential to the end of the flexure arm 304, and the flexure arm 304 is mounted at an angle 328 with respect to the actuator arm 308. This produces a skew angle 332, in one embodiment, of approximately 45 degrees at the outer diameter 320 of the magnetic media 12, and a skew angle 332 of approximately 65 degrees at the inner diameter 324 of the magnetic media 12. It will be understood that other skew angles 332 are possible.

In a similar fashion to the embodiment described above with respect to **Fig. 7**, this embodiment also requires an alternative method of writing servo information to the magnetic media. Such alternatives include pre-printed media, introducing an alternate head to the magnetic media for recording the servo pattern, and a spiral type servo pattern, all of which were mentioned above.

Referring now to **Fig. 9**, another embodiment for giving a head a large skew angle is illustrated. As can be observed, the actuator arm assembly 336 in manufactured such that it is relatively short as compared to a typical actuator arm assembly 340 commonly used in current day devices and represented by the dashed lines. The result of the shorter actuator arm assembly 336 is a relatively large difference in head skew angle between the outer diameter 320 and the inner diameter 324 of the magnetic media surface 12. As can be seen by the solid lines of **Fig. 9**, the skew angle 344 near the outer diameter 320 in this embodiment is approximately 20 degrees. As can be seen by the dotted lines of **Fig. 9**, the

skew angle 348 near the inner diameter 324 of the magnetic media surface 12 is approximately 60 degrees.

In this embodiment, the length of the actuator arm assembly 336 is selected such that the skew angle 344 near the outer diameter 320 is relatively low, with the skew angle 348 near the inner diameter 24 being relatively high. In this embodiment, these angles are selected to minimize track misregistration (TMR) toward the outer diameter 320 of the magnetic media 12. TMR is commonly higher toward the outer diameter 320 due to a number of factors, including disk flutter, which is well understood in the art. Thus, this embodiment results in an effective head width which is wider towards the outer diameter 320 than it is toward the inner diameter 324. Additionally, in this embodiment, the head 300 located on the actuator arm assembly 336 can continue to be used to record a radially coherent servo pattern on the surface of the magnetic media 12.

The above embodiments have been described using MR heads as an example. However, it will be understood that the above would also apply to other types of heads and read/write elements, including GMR type heads.

While an effort has been made to describe some alternatives to the preferred embodiment, other alternatives will readily come to mind to those skilled in the art. Therefore, it should be understood that the invention may be embodied in other specific forms without departing from the spirit or central characteristics thereof. The present examples and embodiments, therefore, are to be considered in all respects as illustrative and not restrictive, and the invention is not intended to be limited to the details given herein.